Sensitivity Analysis with Adjoint of Radiation Code

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The Atmospheric and Environmental Research (AER) Local Forecast and Assimilation (ALFA) model has been coupled with the NASA/Ames rapid model for radiation calculations (Toon et al. 1989). To provide a data assimilation system for the Atmospheric Radiation Measurement (ARM) Program, the adjoint codes of both models have been written. In addition to the data assimilation application (see Louis and Živković, this volume), the adjoint can be used for sensitivity analysis applications. This paper reviews some results of a sensitivity analysis of radiative parameters in the spectral domain and within the context of a general circulation model (GCM).

The adjoint equations allow a direct computation of the sensitivities of a model output to all meteorological and radiation parameters, with a single integration of the nonlinear model and the adjoint model. For example, if one is interested in knowing how sensitive the surface temperature is to the radiation parameters compared with other meteorological parameters, the response function needs to be set to surface temperature. At the end of the adjoint integration, the values of the adjoint variables corresponding to those parameters provide the requested sensitivities. Furthermore, if we know the uncertainties associated with these parameters, the accuracy of the model can be assessed. An example of such a computation is presented in Table 1.

The table compares the sensitivity of surface temperature to various model and radiation parameters in the presence and the absence of cirrus cloud. Spectral sensitivity values are summed over the two regions: the shortwave region (SW), and the longwave region (LW). The units are °K/(time step) for one percent change in the parameter, but what is of interest is the relative magnitude of the results (Hall et al. 1982). The case considered here was based on weather and parameter values for Oklahoma City on June 5, 1992, at 5 p.m. local time, with a surface temperature of 299.2°K and pressure of 982.8 mb. The cloud bottom is located at 9.4 km and the top at 13.9 km. The optical thickness is 6.1. Clear sky calculations involved the same atmospheric vertical structure, but clouds were not permitted to exist.

When the magnitudes of the relative sensitivities are compared, it is noticeable that the largest sensitivities involve the clouds: sensitivity of surface temperature to single scattering albedo and asymmetry coefficient. These are larger than the sensitivity to albedo or emissivity. The presence of clouds also affects the sensitivity to surface parameters like albedo, emissivity, ground heat diffusivity or roughness length. It also increases the sensitivity to the ground heat capacity and CO_2 concentration, but leaves virtually unaffected the other parameters considered.

The diagram in Figure 1 illustrates the distribution of the model sensitivity as a function of IR spectral bands and atmospheric pressure. It represents the absolute sensitivity of the radiative heating rate in the lowest atmospheric layer to the water vapor absorption coefficient. Note that the sensitivity varies with height at different rates for different wavelength bands. This phenomenon is also observed for absorption by other trace gases, i.e., CO_2, O_2 and O_3.

In addition to trace gas absorption, we looked at the sensitivity of model variables to other changes, for example, cloud optical depth. In this case, we found that the surface temperature (Figure 2a) is the most sensitive to changes in the shortwave spectral region because the high cloud blocks incoming radiation. Note that the maximum sensitivity is in the O_3 0.719 µm band, which indicates interaction of clouds with ozone absorption. In the longwave spectral region, the sensitivity of surface temperature to cloud optical depth is rather small and limited mainly to the bottom of the cloud layer. The model temperature in the cloud uppermost layer exhibits a different sensitivity pattern (Figure 2b). The largest sensitivity is found in the longwave

Table 1. Comparison of surface temperature sensitivity to model and radiation parameters in the presence and the absence of an opaque cloud. The units are °K/(time step) for one percent change in the parameter.

Parameter	Clear	Cloudy
Cloud single scattering albedo SW		$0.11e^{-1}$
Cloud single scattering albedo LW		$-0.15e^{-3}$
Cloud asymmetry coefficient SW		$0.90e^{-2}$
Cloud asymmetry coefficient LW		$-0.30e^{-3}$
Cloud optical depth SW		$-0.13e^{-2}$
Cloud optical depth LW		$0.17e^{-3}$
Surface albedo	$-0.74e^{-2}$	$-0.31e^{-2}$
Soil heat capacity	$-0.17e^{-2}$	$-0.71e^{-2}$
Surface emissivity	$-0.84e^{-2}$	$-0.65e^{-2}$
Cloudiness		$-0.68e^{-2}$
Roughness length	$-0.56e^{-2}$	$-0.53e^{-2}$
Deep soil temperature	$0.49e^{-2}$	$0.49e^{-2}$
Turbulence mixing length	$-0.30e^{-3}$	$-0.26e^{-3}$
Ground heat diffusivity	$-0.58e^{-3}$	$0.27e^{-3}$
Max water concentration in soil	$-0.42e^{-4}$	$-0.35e^{-4}$
Ground moisture diffusivity	$-0.14e^{-4}$	$-0.11e^{-4}$
Deep soil moisture	$-0.37e^{-8}$	$-0.31e^{-8}$
CO_2 concentration	$0.73e^{-4}$	$0.90e^{-4}$
H_2O concentration (surface)	$0.30e^{-4}$	$0.30e^{-4}$
O_3 concentration (surface)	$0.46e^{-6}$	$0.48e^{-6}$
H_2O absorption in SW (surface)	$-0.51e^{-5}$	$-0.30e^{-5}$
H_2O absorption in LW (surface)	$0.32e^{-4}$	$0.31e^{-4}$
CO_2 absorption SW (surface)	$-0.15e^{-6}$	$-0.16e^{-7}$
CO_2 absorption LW (surface)	$0.71e^{-5}$	$0.73e^{-5}$
O_2 absorption SW (surface)	$-0.34e^{-14}$	$-0.11e^{-13}$
O_2 absorption LW (surface)	0.	0.
O_3 absorption SW (surface)	$-0.56e^{-7}$	$-0.24e^{-7}$
O_3 absorption LW (surface)	$0.52e^{-6}$	$0.51e^{-6}$

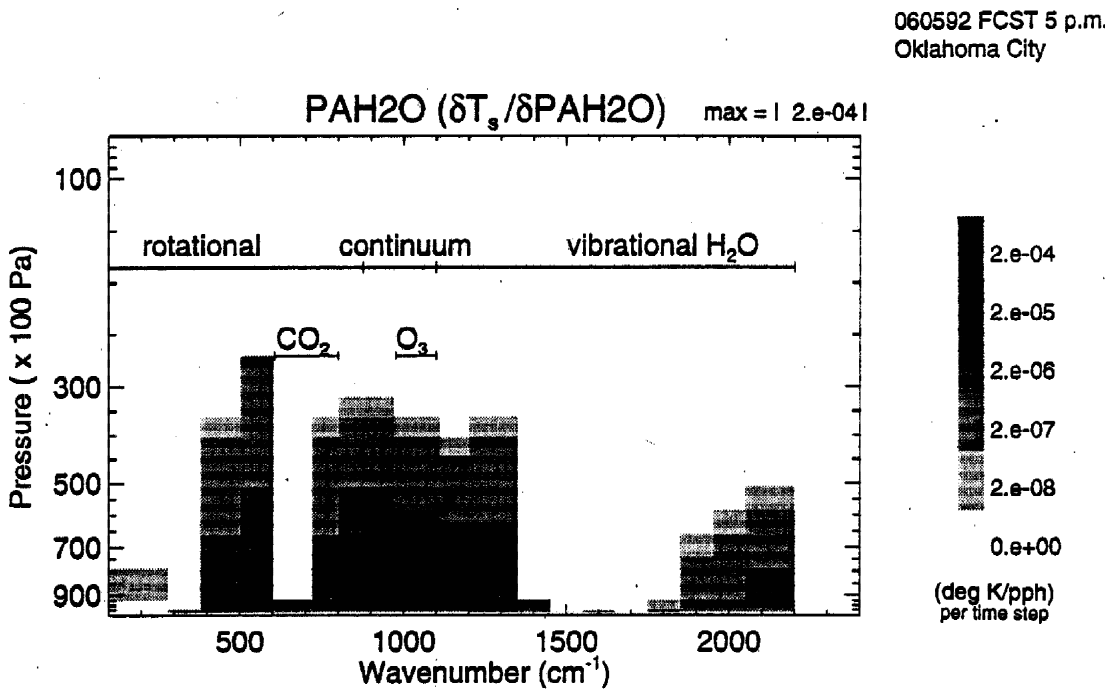

Figure 1. Absolute sensitivity of the heating rate in the first atmospheric layer above the ground to changes in H_20 absorption.

spectral region at the top of the cloud. Large sensitivities that are found in the water vapor shortwave bands are indicative of the interaction of clouds with water vapor absorption.

This is the first sensitivity analysis of this type performed within the context of a GCM. The adjoint technique is a powerful tool that can be used in other applications as well. For example, the model sensitivities presented here can be used to estimate the model accuracy or the significance of observational uncertainties for a GCM forecast. Also, once the model accuracy is established, the sensitivities can be used for "training" of parameterization schemes by better observations.

References

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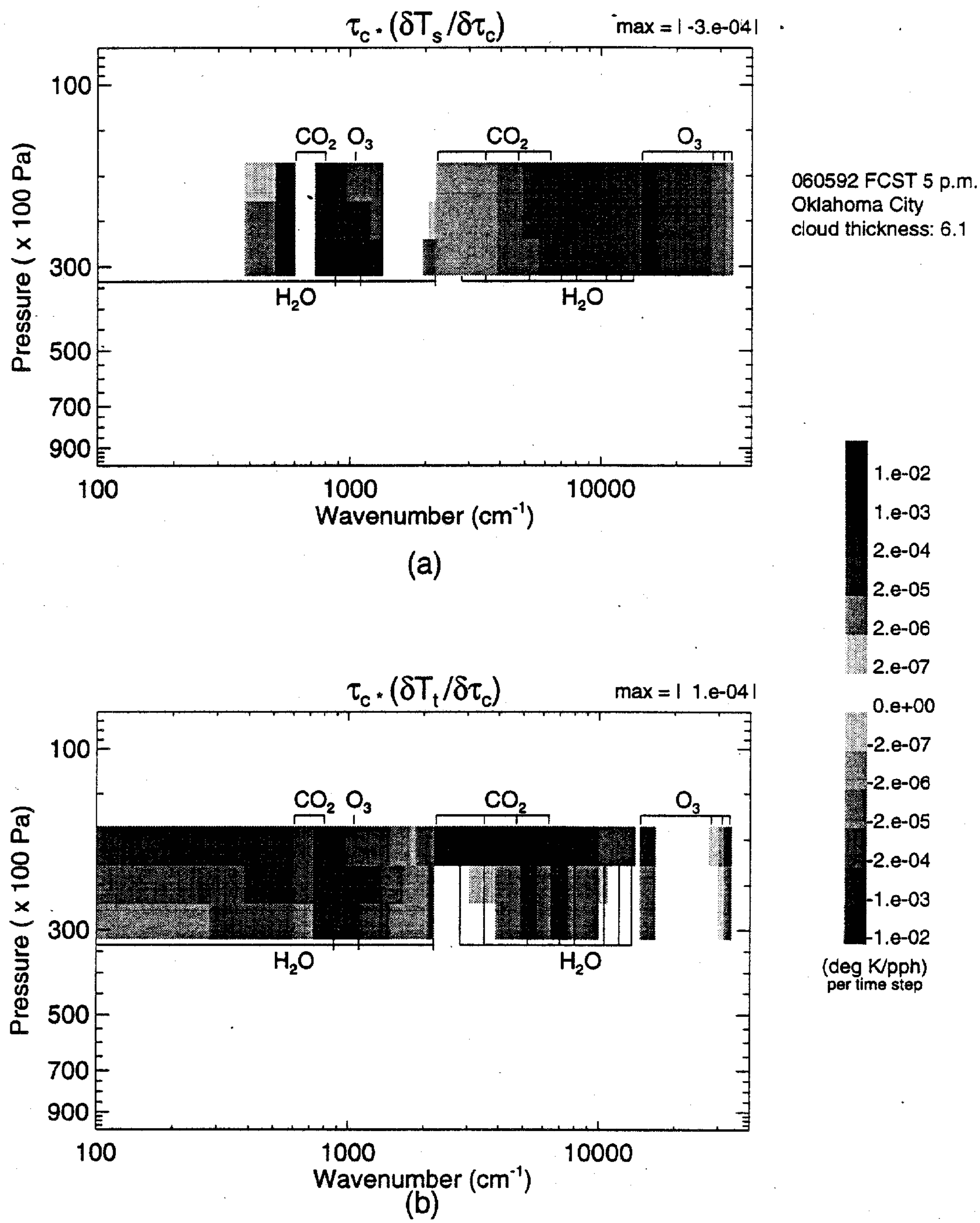

Figure 2. Absolute sensitivity of the surface temperature (a) and the temperature in the uppermost cloud layer (b) to changes in cloud optical depth.